INDUSTRIAL ECOLOGY: A CRITICAL REVIEW

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by

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Abstract

Scientists, policy-makers, and the general public are becoming increasingly aware of environmental damage associated with large and growing material through-put required in modern industrial society. One approach emerging in response to these concerns is called Industrial Ecology (IE). IE signals a shift from "end-of-pipe" pollution control methods towards holistic strategies for prevention and planning of more environmentally sound industrial development. However, the broad umbrella of IE currently houses a diverse group of scholars, consultants, and environmentalists who range in scope from those advocating incremental changes in existing systems, to some promoting a total transformation of industrial activity. This article will present a critical review of the existing U.S. literature on IE. We will introduce and critique IE's primary concepts and analyze weaknesses and "holes" in IE's conceptual framework. We will also discuss the needs and potential for advancing Industrial Ecology concepts and projects in the future.

Keywords: Industrial Ecology, Environmental Policy, Design for Environment

I. Introduction

Industrial activities are increasingly in confrontation with ecological systems. Continued natural resource exploitation and environmental impacts of resource use and pollution are cause for concern around the world. One broad approach emerging in response to these concerns is called Industrial Ecology (IE). IE offers important goals and organizing principles for reforming industry, providing concepts which are gradually being embraced by leaders in industry, academia, and government agencies.

IE signals a shift from "end-of-pipe" pollution control methods towards strategies for more comprehensive prevention and planning of environmentally sound industrial development. IE is advanced as a holistic approach to redesigning industrial activities. However, the broad umbrella of IE currently houses a diverse group of scholars, managers, engineers, consultants, and policy analysts who range in scope from those advocating minor incremental changes in existing systems, to some promoting a total transformation of industrial systems.

This article presents a critical review of the existing U.S. literature on IE. We first introduce IE's primary concepts: modeling industrial systems on ecological principles, closed material cycles, waste exchanges, and Design for Environment. We discuss where and how the literature differs in interpreting the basic concepts of IE. We then analyze the omissions and weaknesses in IE's conceptual framework. Finally, we discuss directions and potentials for advancing Industrial Ecology concepts and projects in the future.

II. Characterizing Industrial Ecology

Industrial Ecology (IE) is currently a broad umbrella of concepts rather than a unified theoretical construct. As such, it is described and presented in different ways by different authors. Based on the authors' perspectives on the current state of industry and the environment, IE can become either an incremental extension of efficiency improvements underway in industry, or a radical new paradigm that must be embraced if we are to save the planet from the impacts of industrial development. Similar to "sustainable development," IE is vague and broad enough to serve as the catchword for many different arguments. This ambiguity of course has benefits as it may lead more people to accept IE as a valuable concept. It also has pitfalls however, as any movement or discipline lacking clarity of goals, objectives, and specific strategies is likely to founder.

In this section, we will characterize IE concepts by briefly analyzing definitions, origins of IE thinking, and interpretations of how to apply IE in practice. IE is defined in very broad terms which range from normative arguments to simple statements of efficiency and logic. The basic concept underlying most of IE is the idea of modeling industrial systems on natural ecosystems. However, even this fundamental concept is interpreted widely by the community of IE enthusiasts. A list of definitions serves to highlight the breadth of interpretations.

Definitions

Frosch and Gallopoulos (1989), two of the earliest U.S. proponents of IE explain that "the traditional model of industrial activity - in which individual manufacturing processes take in raw materials and generate products to be sold plus waste to be disposed of - should be transformed into a more integrated model: an industrial ecosystem. In such a system the consumption of energy and materials is optimized, waste generation is minimized and the effluents of one process...serve as the raw material for another process." For Frosch and Gallopoulos (1992:290), IE serves as "a better system for the coordination of technology, industrial processes, and consumer behavior."

Graedel and Allenby (1995:9) in the first textbook on IE assert that, "Industrial Ecology is the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital."

IE is described as an information driven field in which the advances of the "information revolution" can be harnessed for improving the environmental performance of industry. Frosch and Uenohara (1994:2) explain that "Industrial ecology provides an integrated systems approach to managing the environmental effects of using energy, materials, and capital in industrial ecosystems. To optimize resource use (and to minimize waste flows back to the environment), managers need a better understanding of the metabolism (use and transformation) of materials and energy in industrial ecosystems, better information about potential waste sources and uses, and improved mechanisms (markets, incentives, and regulatory structures) that encourage systems optimization of materials and energy use."

Using ambiguous terms to define IE, Allenby (1992) writes that "industrial ecology may be defined as the means by which a state of sustainable development is approached and maintained. It consists of a systems view of human economic activity and its interrelationship with fundamental biological, chemical, and physical systems with the goal of establishing and maintaining the human species at levels that can be sustained indefinitely - given continued economic, cultural, and technological evolution." Lowe (1993) similarly argues that "Industrial Ecology is a foundation for creating sustainable industry in a sustainable society," employing a "whole systems approach to design and management of the industrial system in the context of local ecosystems and the global biosphere."

Socolow argues that "Industrial ecology is a metaphor for looking at our civilization," which provides perspectives on long-term habitability, global scope, the overwhelming of natural systems, vulnerability, mass-flow analysis, and centrality of the firm and the farm (Socolow 1994:3). For Socolow, as for many other proponents of IE, the perspectives of IE "add up to ënew thinking'".

Tibbs (1992) and Ehrenfeld (1994) have laid out what they consider the basic components of IE, which we will discuss in more detail below. Ehrenfeld's list (based on Tibbs 1992) of the seven components of IE (Ehrenfeld 1994:16) is useful as a base for discussing which concepts different authors accept or consider critical to IE. This list includes: (1) improving metabolic pathways for materials use and industrial processes; (2) creating loop-closing industrial practices; (3) dematerializing industrial output; (4) systematizing patterns of energy use; (5) balancing industrial input and output to natural ecosystem capacity; (6) aligning policy to conform with long-term industrial system evolution; and, (7) creating new action-coordinating structures, communicative linkages, and information.

Origins

As the definitions show, Industrial Ecology has come to represent a broad set of concepts, tools, analogies, and visions for carrying out organized changes in industrial systems. The origins of IE are based in many fields and past trends in environmental and industrial movements. What IE claims to offer are connections among different fields or systems of thinking - bringing systems thinking in ecology together with systems engineering (for design of products and processes) and economics.

Much of the terminology of IE comes out of ecological sciences and systems analysis. The ecosystem analogy is at the center of most papers on IE, where proponents discuss modeling the development and behavior of industrial systems on patterns of natural ecosystem evolution. Common aspects of ecosystems which are discussed include: closed materials cycles, evolutionary principles, resiliency of systems, and dynamic feedback. Some authors also extol the linkages between cooperation and competition in ecosystems.

These concepts and constructs are by no means new. Barry Commoner in his seminal book, The Closing Circle (1971) argued for the relationships between modern industrial activity and ecology, laying out the "laws" of ecology as they relate to current human activities. Commoner argued in 1971 that "if we are to survive economically as well as biologically, industry, agriculture, and transportation will have to meet the inescapable demands of the ecosystem" (p.282). These ecosystem demands include "essentially complete containment and reclamation of wastes...essentially complete recycling of all reusable metal, glass, and paper products; [and] ecologically sound planning to govern land use". Commoner goes on to assert that "present productive technologies need to be redesigned to conform as closely as possible to ecological requirements," (p.283) a very IE sounding prescription.

On the industrial planning side, Europeans led a movement for "low-" and "non-waste" technologies in the 1970's. At a conference on non-waste technology, Royston (United Nations 1978:39) argued for "technology based on the conceptualization of the total system of raw material supply-production-consumption-disposal and recycling, viewed in an integrated and a systemic fashion so that no waste occurs." Schmitt-Tegge (United Nations 1978:53) describes non-waste technology in terms almost synonymous with IE - using materials and energy more economically, reducing pollution, increasing re-use and recycling of materials within production, and extending the life of products. Royston noted in 1978 that the strategy discussed by many IE proponents in the 1990's of "producing a useful by-product instead of an environmentally degrading waste product is not new". Fischer (United Nations 1978:669) describes environmental programs sponsored by the German government in the early 1970's that included the goal of "improved use of raw materials" through: use of by-products, decreased material intensity, reduced production losses, and increased product lifetime.

A number of IE authors trace the term "industrial ecology" to a program sponsored by the Japanese Ministry of International Trade and Industry (MITI) in 1971 (Watanabe 1994) which promoted "principles of industry-ecology" such as recognizing system boundaries for industrial activities, understanding industry-environment interactions, recognizing redundancies and response relationships in systems, and developing mechanisms of control over human activities to promote ecological equilibrium.

Another component of the IE literature comes directly from analysis of "industrial metabolism," and in particular work done by Ayres (1989, 1991). Industrial metabolism focuses on analysis of materials stocks and flows, and potentials for reducing materials and energy dissipation in the environment. Ayres' work on tracking materials flows and promoting increased recovery/reconditioning/reuse/recycling is often cited as a cornerstone of actually implementing IE.

Interpretations

While there are a number of basic components of IE that all authors mention, there is a wide spectrum of interpretations of IE's goals and strategies. On one end of the spectrum are people who look to IE as an incremental approach to dealing with environmental problems, focusing largely on efficiency improvements. At the opposite end are those who see IE as the basis for a major transformation of industrial society, and a goal to strive for.

As with any new trend or buzzword, some individuals are attempting to co-opt IE so that it comes to mean nothing more than the status quo. For example, Linden (1994) in an argument for continued use of fossil fuels writes "from an industrial ecology viewpoint, it appears that the global energy system, while contributing a large share of dissipative material flows in the biosphere, also has sufficient flexibility and technology development potential to keep its environmental impact within acceptable bounds." Linden represents a group of technological optimists who see IE as a means of better planning and technology development that will help solve many of the current environmental problems that planning and technology have created. In an attack on scientists and environmentalists who are concerned with global warming, Linden supports IE as one tool in "the task of managing the transition to a sustainable global energy system that can satisfy human needs over the indefinite future with minimal environmental impact," and will help avoid the "need to curtail greenhouse emissions from fossil fuel use beyond the sizable reductions inherent in the pursuit of least-cost energy service strategies" (Linden 1994:57).

Even more questionable are representatives of resource extraction industries who argue for re-thinking IE to make what they have always done seem part of IE. Chiaro and Joklik (1994:1) argue that industries such as coal mining can meet the goals of IE if you "view the extractive industry as its own system, minimizing the amount of energy and resources that go into extracting the commodities in question and minimizing the amount of waste products that are created in the production of the raw materials." By drawing the IE box small enough, anything it seems can be an optimized industrial ecosystem. These IE proponents assert that what is needed to develop IE concepts in their industries is for the government to advance a "more voluntary, incentive-driven approach" (Chiaro and Joklik 1994:6) which will help industry be more creative and proactive. This however, has been viewed by some environmentalists as a rationale for weakening environmental regulations.

A small group of writers see IE as a concept that primarily serves to assist their industry or organization make money. (This view is problematic for a number of reasons but primarily - for the purposes of this paper - because it serves to further cloud the basic concept of IE.) Torrens and Yeager (1994) use IE as a means to argue for "environmentally beneficial use of electrotechnologies in other sectors of the economy," which is exactly the goal of the electric power industry and the Electric Power Research Institute (EPRI) for which they work. After discussing IE and the electric power sector, the authors surmise that "electricity can play a vital role in achieving economic growth and sustainability without sacrificing environmental quality," and we are further informed that "the benefits of technological innovation made possible by electricity" will be the basis for sustainable development around the world (1994:25), a point which is no doubt more comforting for the power industry than for people concerned with ecological sustainability.

Several general trends in thinking have emerged among those authors that are discussing IE in a substantive way. The first focuses IE on single company changes in production processes to prevent pollution, increase energy efficiency, improve recycling and recovery, as well as improve efficiency of production. This brand of IE stresses re-designing industrial products and processes to meet environmental goals.

Within this framework, pollution prevention - a well-established industrial-environmental strategy - is presented as the key to IE. Patel (1992) describes IE as a "cradle-to-grave production philosophy, except that in an ideal circumstance there is no grave." Patel's six elements of IE all relate to process and product changes within an individual firm, from just-in-time delivery systems that reduce inventory and waste of hazardous inputs, to engineering controls to assure robust processes. DFE (which we discuss in detail below) is sometimes described as a pollution prevention tool for product designers to improve product and process designs with respect to their environmental impacts while simultaneously increasing profits (Paton 1994). Product stewardship and corporate product responsibility programs relate to efforts to take greater responsibility for the full life-cycle impacts of products (Dillon 1994:203).

As Frosch and Gallopoulos assert, "the industrial ecosystems approach to manufacturing begins with individual process optimization." Process optimization is interpreted as the core of environmental protection; the more efficient use of materials, energy, and capital will reduce environmental impacts. However, they do acknowledge that single company activities will not solve all environmental problems, and thus the "ideal industrial ecosystem ...requires the integration and coordination of industrial processes and subsystems to closely resemble the functioning of biological ecosystems" (Frosch and Gallopoulos 1992:288).

This need for subsystem integration and coordination leads to calls for "closing loops" and expanding systems of waste exchanges. Material closure is extended beyond material reuse and recycling within firms, to "closed-loop systems" where the system boundaries are defined much more broadly. Allen (1994) argues that it is possible to think of "wastes as raw materials" and that "extensive waste trading could significantly reduce the quantity of waste requiring disposal." Tibbs and Lowe (and almost every other IE proponent) portray Kalundborg, Denmark, as a model of waste exchanges between firms. Kalundborg represents an informal system of material and energy "cascading" between firms, where wastes from one factory are piped and used in a nearby industry.

While the implementation of IE is rather limited, several authors have argued that IE is central to "sustainable development" (see Ehrenfeld, Lowe, Allenby, Socolow). These authors advance goals of bringing industrial development into balance with natural and social systems, integrating human and "natural" systems by design. IE is thus placed as part of a paradigm shift. Lowe and others describe IE as critical to the "goal of industrial transformation... [and] fundamental system-wide change in a longer time frame" (Lowe 1993). Tibbs notes that "the ultimate driver of the global environmental crisis is industrialization, which means significant, systemic industrial change will be unavoidable if society is to eliminate the root causes of environmental damage" (Tibbs 1991:1).

As we will discuss in more detail below, a large gulf separates descriptions of what IE can be, and specific examples and strategies for implementing IE. We believe IE is an important (although still emerging) framework of goals and strategies for reforming industry. We will thus describe and constructively critique IE on three levels in the following section: specific strategies for implementation, the disconnect between strategies and goals, and omissions and weaknesses in current constructs.

III. Strategies and Tools

Early contributors to IE have sought to provide broad strategies as well as specific tools to bridge the gap between process-specific waste prevention activities and broader visions of sustainable industrial practice. Many of the tools suggested are based on the idea of achieving what Graedel and his co-authors call a "systems-oriented" approach to product and policy design (Graedel, et al. 1993:18). Depending on how a "systems-oriented" approach is interpreted, these techniques generally support one of two strategies: (1) the provision of information that will allow broader environmental consequences to be incorporated into the decision making process at levels ranging from policy to product design (i.e. "getting the information right"), and (2) the monetary incorporation of externalities that prevent the market from properly coordinating material flows (i.e. "getting the prices right"). In this section, we will characterize these two strategies and address methodological weaknesses in several of the tools that are advanced.

Getting the Information Right

The first interpretation of achieving a systems-oriented approach stresses the need for designers to consider the broader environmental implications of their decisions. The underlying premise is that industry needs more information about the environmental implications of their activities, and that by better analyzing production it will be possible to re-design products and processes to save money and protect the environment. Emphasis in IE is placed on achieving a "holistic approach" (Frosch and Gallopoulos 1990:107) to product design by using what Lowe calls "analytic and modeling tools" (1993:73) to incorporate a wide range of environmental concerns into the design process. Several specific tools for analyzing systems-level issues have been discussed in the IE literature: Design For Environment (DFE) and its counterpart Life Cycle Assessment (LCA), Industrial Metabolism (IM), Input-Output (IO) models from the field of structural economics, and "Ecofeedback". We will focus our critique on DFE and "Ecofeedback" analyses as they are strongly emphasized (and promoted) in the IE literature and both possess several important methodological weaknesses.

Design for Environment

To improve on current design techniques which fail to consider broad environmental implications of products (and the processes that create them), several authors - but especially Allenby and Graedel - have supported the implementation of DFE as a means to "integrate decision making across all environmental impacts of a product" (Lowe 1993:80). According to Allenby, "The idea behind DFE is to ensure that all relevant and ascertainable environmental considerations and constraints are integrated into a firm's product realization (design) process" (Allenby 1994b:139). In practice, Graedel and Allenby have suggested that DFE would involve the use of matrices to qualitatively account for a wide range of environmental impacts corresponding to various stages of a product's life cycle. Such matrices could then be used to compare the broad environmental implications of various process and product options. (Graedel and Allenby 1995).

The benefits of this approach have been highly touted throughout the IE literature as a way not only to design environmentally preferable products, but to increase inter-firm coordination of materials use (through waste exchanges) and to cause favorable shifts in industrial material and energy use patterns. Allenby asserts that "in the short term, Design for Environment is the means by which the still vague precepts of industrial ecology can in fact begin to be implemented in the real world today" (Allenby 1994a:26).

For at least two reasons, these expectations appear to strongly over estimate DFE's ability to improve the environmental performance of products. Firstly, it is doubtful that massive (and costly) data requirements would yield decisive information about any product more complicated than a Styrofoam cup (Hocking 1991). Any effort to consider "all the potential environmental implications of [a] product or process" (Allenby and Fullerton 1991-92:55) would generate a barrage of formidable tradeoffs between uncertain and widely disparate outcomes that must ultimately be reduced to social value judgments (Allenby 1994a:28). Which, for example, is worse, localized air emissions that impair worker health or global emissions that may harm future generations? Allenby's suggestion of using an "unambiguous, if general risk prioritization" (1994a:28) and an international "materials database system" to allow materials choices to objectively "reflect broad social consensus" (1994a:27) seems highly problematic. Conflicts regarding environmental justice, international equity, and the incomparability of disparate situations will severely limit our ability to distinguish benefit from harm and therefore limit DFE's ability to provide unambiguous prescriptions for product or process "improvement".

Secondly, although these analyses have been proposed as a way to help companies see the "bigger picture," it is likely that industry will become enmeshed in complicated trade-offs regarding minute aspects of complicated products and miss entirely the need for fundamental changes in broader technological infrastructures. A team of design engineers may struggle for months over whether it is environmentally "preferable" to use an aluminum or a plastic radiator-cap while more fundamental questions about the sustainability of the gasoline-powered automobile are never raised. While smaller changes in product and process design can certainly be helpful, efforts to design "for the environment" risk loosing sight of the forest for the trees.

"Ecofeedback"

Lowe and Tibbs have also suggested that industries use "Ecofeedback" systems to support the "adjustment of [industrial] operations in response to real time information about current environmental conditions" (Lowe 1995:13). Although our ability to observe subtle changes in natural ecosystems continues to expand, the idea of using "real time information about environmental conditions" (Tibbs 1992:10) as a basis for regulating industrial emissions is at best an exaggeration of current monitoring abilities that detracts from the credibility of the IE literature, and at worst a reckless assertion that belies the complexity of the earth's ecosystems. It should be clear that the consequences of today's emissions cannot always be observed today - the destruction of the ozone layer resulting from CFC emissions being one obvious example.

Even more problematic, however, is that environmental feedback systems are techniques for implementing an approach to waste reduction that focuses on "managing the interface between industry and the natural environment," and obtaining a "detailed understanding of ecosystem assimilative capacity and recovery times" (Tibbs 1992:10). Frosch and Uenohara even suggest the need to "restore and improve the assimilative capacity of the environment" (Richardson and Fullerton 1994:3). Although the meaning of "restoring" and "improving" assimilative capacity is not defined, an ecosystem's capacity for waste can only be increased through the implementation of waste treatment and dispersion strategies or waste accommodation strategies (such as adding lime to lakes in an effort to increase their acid buffering capacity). These are the very strategies IE is trying to overcome. Implicit in these approaches is the acceptance of emission rates that do not exceed estimated assimilative capacities. Aside from the extraordinary difficulty (and subjectivity) that plagues even sincere efforts to estimate an ecosystem's "capacity" for waste, these end-of-pipe strategies miss entirely IE's emphasis on preventive approaches to reducing material throughput.

Getting the Prices Right

A different approach to achieving "systems-oriented" product and policy design seeks to supply information indirectly by incorporating environmental externalities into market prices. In this approach, the market is seen as an existing - but flawed - tool for coordinating decisions along economic principles of efficiency. The issue becomes not whether we can develop sufficient analyses to incorporate system-wide considerations into decision making, but whether "the normal economic mechanism will fail to coordinate the interconnected system..." (Nordhaus 1992:843). From this point of view, we simply need to ensure that the market can properly coordinate decisions by correcting market flaws that skew price signals.

Strategies for correcting market failures fall broadly into two categories: removing barriers that prevent private industry from responding to existing price signals, and addressing market externalities that lead to incorrect price signals. In the first category, several regulatory and legal constraints such as liability clauses and regulations that ostensibly prevent corporations from pursuing existing (economic or value-based) incentives to reduce waste are addressed (Allen 1993; Frosch 1994; Weinberg, et al. 1994). Other problems such as organizational and information deficiencies that distort market signals have received far less attention in the IE literature.

In the second category, nearly every paper written on IE has proposed the use of Pigovian taxes on virgin raw materials or market-based policies such as tradable permits to incorporate environmental externalities into prices. Frosch, for instance, argues that we need to "internalize environmental costs" (1992:802), Ayres states that "new economic incentives - e.g. higher prices or taxes on undesirable activities - are needed" (1991:21), Nordhaus asserts that "[externality pricing can turn] the economy into the economic equivalent of a closed ecological system" (1992:850), and Tibbs claims that "probably the primary policy concern [for IE] is the resolution of the extensive debate in recent years about the need to reflect the real costs of environmental degradation in market pricing" (1992:16). Policy tools for incorporating the "real cost of environmental degradation" have been a part of IE since Frosch and Gallopoulos first suggested the use of "fees and taxes for pollution" that could "if suitably set...be an effective means for manufacturers to incorporate societal costs of pollution and waste into their cost accounting systems" (Frosch and Gallopoulos 1990:107).

Unfortunately, the enthusiastic and usually cursory promotion of pricing strategies paints a false picture of "newness" and "simplicity" over problematic policy tools that have been the focus of heated debate for decades. The first of several important problems with "getting the prices right" is the dilemma of placing monetary value on things such as environmental aesthetics or biodiversity that cannot be monetarily valued. Nordhaus, in a paper explaining the benefits of pricing strategies, acknowledges "the practical difficulties that arise in implementing externality pricing" (1992:850). Formidable barriers would seem a more appropriate term. Graedel and Allenby explain that "numerous valuation problems make cost/benefit analyses difficult: how to identify and properly quantify social costs; how to treat moral and ethical considerations; how to make decisions when data on impacts are so sparse and uncertain" (1995:87). This strategy also neglects the realities of the globalizing world economy and the associated barriers to the effectiveness of pricing strategies. Efforts to monetarily incorporate environmental externalities in today's world market could, for example, lead to international outsourcing or be interpreted as a barrier to free trade. As Schnaiberg argues, in a number of ways "ëgetting the prices right' flies in the face of a transnationally-competitive market system..." (1994:12).

IV. Disconnect Between Strategies and Goals

In this section, we will introduce a second layer of critique by asking whether the strategies discussed above - notwithstanding the methodological weaknesses of their constituent tools - are constructed on accurate perceptions of the principal barriers to achieving IE's goals and hence whether their successful execution would indeed help advance these goals. As discussed in the beginning of this critique, defining IE's goals is problematic in itself since different people have expressed widely different interpretations of what these goals are. Nevertheless, among those advancing the stronger, transformative interpretations of IE, two broad goals are generally advanced: first, achieving closed material cycles; and second, realizing a fundamental paradigm shift in our thinking about industry-environment relations.

Closing the Loop

The first of industrial ecology's two broad goals is to establish near-closed material cycles analogous to those found in natural ecosystems. According to Lowe, "The ultimate goal of industrial ecology is bringing the industrial system as close as possible to being a closed-loop system with near complete recycling of all materials" (1993:75 emphasis added). Ayres argues further that, "unless the product cycle and the materials cycle are (very nearly) closed, the [industrial] system as a whole will continue to be unsustainable" (1991:21). A crucial test for IE, therefore, is to determine whether the successful implementation of the market and information strategies discussed in the previous section would advance - or at least not inhibit - this urgent goal. We begin with the market.

Notwithstanding the formidable task of pricing the unpriceable, "getting the prices right" could indeed advance IE's first goal. The reasoning underlying this strategy is straightforward: private industry is in the business of maximizing profits. Incorrect price signals that fail to incorporate environmental externalities misdirect these efforts, making cleaner industrial practice less profitable. It follows directly that industry will respond favorably to market strategies that make it more profitable to be less polluting. The two assumptions underlying this reasoning - that private industry will reduce its waste if doing so will increase its profits, and that the prices of raw materials and energy seldom reflect the environmental externalities associated with their production - are widely accepted. Incorrect price signals are not, however, the only problem that skews decision making in private industry. Significant organizational and information deficiencies that can impede industry's ability to respond even to correct price signals need to be addressed as well. Nevertheless, if the methodological constraints could be overcome - "a very big if!" as Nordhaus admits (1992:850) - economic incentives such as virgin material or pollution taxes would indeed help close material cycles.

Unfortunately, the extent to which "getting the information right" will support the goal of achieving material closure, is more limited. Certainly "Ecofeedback" will not help advance this goal since it focuses on managing open material flows. In addition, DFE may not advance the closure of material cycles since it appears to address the wrong problem. DFE seeks to provide industry with the analyses and procedures necessary to incorporate "systems-oriented" information into the design of environmentally preferable products. The problem this strategy addresses, therefore, is a perceived inability on the part of the design engineer to incorporate broader environmental considerations into product design. This strategy however ignores a larger question: if the necessary analyses were made available, why would they be used? While some authors have mentioned that regulatory policies such as mandatory product take-back or labeling programs would be required to encourage DFE, the proposed policies - and the means by which they would encourage (or enforce) DFE - are not well described (Allenby 1994a, 1994b; Graedel and Allenby 1995). The IE literature delineates procedural aspects and potential benefits of systems-oriented procedures such as DFE but mostly assumes - wrongly we believe - that industries will have financial or value-based motivation to use these analyses. We look initially at two avenues of financial incentives that have been suggested.

First, Allenby (and others) propose that companies might adopt systems-oriented strategies in order to satisfy a growing demand for "green products" (Allenby 1994b:140). This proposal is typical of the off-hand approach to social issues in the IE literature. Since the 1980s, researchers have been pointing out the limitations of green marketing (Plant and Plant 1991). Furthermore, even if demand for greener products were strong, a company would not need to realize meaningful changes in its product design to bolster a "green" image. The second avenue of financial incentive is more plausible but still problematic. Several authors such as Paton suggest that DFE could be used to produce "environmentally responsible products [that] provide a measurable source of competitive advantage and business success by: contributing to revenues profits and growth..." (Paton 1995:350). Graedel and Allenby similarly argue that companies should view these approaches as "strategic to the firm in the same sense as competitive or economic considerations" (Graedel and Allenby 1995:311). In these arguments, DFE is interpreted as a design-oriented pollution prevention strategy that could provide novel approaches to reduce wastes and increase profits.

This interpretation seems to miss the stated point of DFE. While industry-wide pollution prevention activities have clearly demonstrated that environmental improvements in plant operations can indeed be profitable, the systems-oriented analyses described in the IE literature seek to go beyond the single factory perspective of traditional P2 activities and optimize environmental variables that lie beyond the realm of environmental stressors that the individual firm is traditionally responsible for. Indeed, the whole thrust of industrial ecology is to move "beyond individual company or plant boundaries to seek improvements in performance of larger systems" (Lowe 1993:76). At this "larger systems" level, the pollution prevention pays ideology does not apply. It is by no means certain that efforts to optimize environmental performance beyond the realm of an individual firm - and hence the realm of an individual firm's financial liability - would increase profits.

The other motivation suggested for DFE - aside from direct regulatory intervention in the design process - is based on environmental values. Indeed, Tibbs has proposed that information tools such as DFE may be adopted out of value-based motivation. Tibbs proposes that the emergence of a new environmental paradigm - what he calls "corporate environmentalism" (Tibbs 1992:7) - will motivate companies to "accept the environmental imperative and willingly assume the mantel of environmental leadership" (Tibbs 1992:8). Current trends in industry, however, seem to contradict this claim. As Schnaiberg indicates, "...it is hard to accept Tibb's view that corporations are ëgreening' in the face of... growing indebtedness... the threat of [hostile] take over ... ëdownsizing'... ëoutsourcing' ... and globalizing trade" (Schnaiberg 1994:12). While a wide variety of economic, regulatory, and even value-based motivations have driven many industries to clean up their act, the IE literature provides only anecdotal evidence that these actions are based on "greening" corporate agendas.

In addition, even if value-based decision making were on the rise, it would lead to optimization of "beyond the factory" variables only if value-based decision making could sway price-based decision making. While value certainly outweighs profit in specific instances, it is nevertheless doubtful that value-based decision making will play a significant role in realizing IE's broad "goal of industrial transformation" (Lowe 1993:73). Allenby describes the corporate dilemma well: "...private firms, especially in the United States, legally are only supposed to worry about making money. They are not supposed to set values for the country or act altruistically against their financial interests, no matter what the gain to society as a whole...". While publicly held firms are indeed expected to maximize returns on their stock holders' investments, Allenby is correct to add that "in practice, this [legal requirement] is somewhat blurred" (Allenby 1994a:28). But beyond the latitude provided by this blurriness, corporations predominantly follow the market signals they receive. Even if value-based decision making were becoming more important, it is unlikely that this blurriness would provide room for significant improvement in product design.

Realizing a Paradigm Shift

IE's second goal is to bring about a paradigm shift in relations between industry and the environment. This goal goes beyond measurable reductions in material throughput and focuses instead on the ways we perceive industries and their interactions with the natural ecosystems that ultimately support them. Several authors have emphasized the importance of cultural and cognitive changes if IE is to bring about "fundamental system-wide change" (Lowe 1993:73). Graedel and Allenby note that, "Technology alone cannot achieve the transformation we envision; it must work within the societal system to move closer to that goal" (Graedel and Allenby 1995:338). They also emphasize that "the fundamental point is that over time, implementation of industrial ecology and migration toward sustainable development will involve significant and difficult cultural, religious, political and social change" (Graedel and Allenby 1995:60). Most notably, Ehrenfeld has argued not just for the importance but for the necessity of "deep-seated changes in the underlying culture of all the important societal institutions" (1994:33). While the exact nature of this paradigm shift is not clearly expressed in the IE literature, it nevertheless has important implications for the form and intention of IE. These authors are suggesting that IE means more than just closing material cycles; IE encompasses changes in the way we think. Unfortunately, the strategies proposed thus far do little to advance this second goal and in some instances may even impede it.

Following the arguments presented above, it should be clear that "Ecofeedback" will not advance IE's second goal since it encourages both the acceptance of open material flows that don't exceed an ecosystem's "capacity" and an "end-of-pipe treatment and dispersion" philosophy of waste management. It is also unlikely that DFE will advance IE's second goal. We have argued above that industry will not have the motivation to implement changes in product design based on information that does not conform to "pollution prevention pays" criteria. In addition, even if DFE procedures were adopted, efforts to account for the broad environmental implications of a single component of an inherently dirty technology will not necessarily give rise to questioning the fundamental sustainability of the technology. Nevertheless, encouraging engineers to think about the broader implications of product design- even if the focus of the analyses is misplaced - would be better than relying solely on market strategies that may indirectly discourage this type of thinking.

Efforts to adjust market signals by incorporating the costs of environmental externalities are seeking not to change the way we think but rather to improve the coordination of price-based decision making without the need to change the way we think. As Ausubel indicates, "The challenge [for market strategies] is to bring into compatibility the possibly conflicting decentralized decisions, ideally without the necessity for the individual or even institutions to bear in mind the logic of the whole system" (1992:882 emphasis added). Market strategies will not - and indeed cannot - help advance IE's second goal of realizing deeper learning. Indeed, they could inhibit it. Getting the prices right will give industry the incentive to be less polluting and to be less concerned about the environmental consequences of their actions. This dilemma, however, reflects deeper conflicts in capitalist economics and is not easily resolved. As Robert Heilbronner writes, a "serious objection [to economic-driven behavior] is that a general subordination of action to market forces demotes progress itself from a consciously intended social aim to an unintended consequence of action, thereby robbing it of moral content" (Heilbronner 1993 cited in Ehrenfeld 1994:8). Resolving this conflict would require fundamental changes in our system of economics that most proponents of IE would oppose.

V. Implementing Industrial Ecology?

In an effort to substantiate the principles of IE, the literature offers numerous case studies that ostensibly demonstrate their implementation. Some examples such as the industrial metabolism of platinum and iron do indeed exemplify the beginnings of cyclical material flows (Frosch and Gallopoulos 1990). However, many of the examples intended to show how industrial practice can change to conform to IE principles consist of technical or operational modifications for reducing waste streams directly associated with individual processes (see Frosch 1994, Jelinski 1992, Frosch and Gallopoulos 1990). While these efforts certainly help to reduce material throughput, they do not capture the inter-industry, systems-oriented approach to waste reduction that ostensibly separates IE from current pollution prevention activities. In addition, the few examples of inter-industry coordination that are offered - such as the "industrial ecosystem" in Kalundborg, Denmark (Lowe 1993, Tibbs 1992) or the ARCO refinery in Los Angeles (Frosch and Gallopoulos 1990) rely mostly on cascading high entropy wastes into higher entropy feedstocks, a practice which can reduce material throughput but does not conform with - and indeed may even inhibit - IE's goal of achieving closed material cycles. In this section, we will discuss the extent to which these two (ostensible) forms of implementing IE - pollution prevention and material cascading - advance IE's principles.

Pollution Prevention

Pollution Prevention (P2) is often discussed as a component or example of IE practices, involving "the use of materials, processes, or practices that reduce or eliminate the creation of pollutants or wastes at the source. It includes practices that reduce the use of hazardous materials, energy, water, or other resources and practices that protect natural resources through conservation or more efficient use" (EPA 1990). P2 has been applied almost exclusively at the factory level through the use of waste audits, pollution prevention plans, technical assistance programs that provide information on cleaner processes, information clearinghouses, and research into alternative production methods or product designs (Freeman, et al. 1992). IE proponents use examples of P2 such as the replacement of CFC's or no-clean soldering techniques to show that IE is being implemented.

The underlying premise of the P2 movement is that industry needs more information on the inefficiencies of current production methods, and that by better analyzing production it will be possible to re-design products and processes to save money and protect the environment. Further, by pointing out the economics of preventing pollution, it is assumed that industry will choose to do the economically rational thing and reduce wastes. P2 however, has been only partly successful in bringing about changes in industrial practices, and many examples remain of changes that are rational from a P2 perspective, but which firms have chosen not to implement.

Hirschorn and Oldenburg (1988, 1991) have examined barriers to the implementation of P2 and note that "non-technical factors include: competing production priorities, belief that legally required pollution control is good enough, lack of management support to allocate people's time and capital for waste reduction, lack of rewards for successful waste reduction, accounting systems which do not allocate total environmental costs to production profit centers, incomplete data on the exact sources and amounts of environmental wastes, and the difficulty of simultaneously spending resources on regulatory compliance and waste reduction." The experiences of P2 should serve as lessons for successful implementation of IE strategies, and show that simply providing information on "cleaner" or more efficient production processes does not guarantee change will occur in industry.

Cascading Wastes

While the idea of using the waste of one industrial process as feedstock for another can certainly help reduce (or at least slow the growth of) dissipative material throughput, two important drawbacks - the lack of "entropy cycling" and the risk of increased "stiffness" in technological infrastructures - have not been addressed. We will begin our discussion of these drawbacks by briefly developing the concept of "entropy cycling."

As Ayres has indicated, our current industrial system "starts with high quality materials (fossil fuels, ores) extracted from the earth, and returns them to nature in degraded form" (Ayres 1994:25). From a thermodynamic view point, this predominantly open or linear flow of materials through the economy can be conceptualized in terms of the entropy changes that materials undergo as they are converted from virgin resource to waste. In broad terms, this flow can be depicted as a two step process: In the first step, high entropy resources such as mineral and metal ores are refined into low entropy, primary materials. In the second step, these primary materials are consumed through a wide variety of uses and eventually returned to the environment as high entropy industrial or post-consumer wastes. The direction of entropy change in the consumption stage mirrors that of the refining stage. Thus, to create a "closed" material cycle, the first step of the linear flow model must be replaced with an analogous waste recovery step that refines high entropy wastes back into low entropy raw - or "recovered" - materials. Material cycling therefore requires "entropy cycling."

The need for closed entropy cycles in the establishment of closed material cycles is expressed indirectly in both Jelinski's inclusion of a "waste processor" (1992:794) in his four node model of a closed, "Type III" industrial ecosystem (Jelinski 1992:793); and in Frosch's acknowledgment of the "negentropy" (1994:66) necessary to recover materials from waste streams. The importance of entropy cycling is not, however, reflected in the popular idea of using direct waste exchanges that allow waste streams of some industrial processes to be used as feedstocks for others. Frosch has called this type of waste exchange "cascading" since materials figuratively cascade from high entropy waste streams to higher entropy - or "degraded" - feedstocks elsewhere in the economy (Frosch 1992:801). Several authors have misinterpreted the idea of industrial waste exchanges as a technique for closing material cycles. Ehrenfeld states that, "The [material] loop is closed by routing waste materials (and energy) from the source of those wastes to other entities that use them as feedstocks" (1994:18). Lowe, in describing the material cascades that join several industries in Kalundborg, Denmark praises the "web of recycling and re-use" that has been established (Lowe 1995:16).

While waste cascading does offset the demand for other virgin resources, it is important to realize that material cycling can only be achieved by returning wastes to their refined (low entropy) state. Entropy losses do not need to be entirely recovered in only one cycle, and the recycled material need not be used for the same product in each cycle, but to achieve a closed material cycle, all entropy increases must eventually be compensated for. Thus, while cascading material exchanges will certainly reduce rates of material throughput, they are still "open," non-cyclical flows and therefore do not "...demonstrate that industrial ecology's principles can work" as Edington has suggested (1995:32). The IE literature needs to emphasize that shifting toward closed material cycles will require not just discovering higher entropy sinks for existing waste streams but also investing in separation and reprocessing technologies that refine wastes (by "consuming" energy - or more precisely exergy) and return them to the economy as low entropy feedstocks (Brodyansky, et al. 1994).

Our second concern about direct - or cascading - industrial waste exchanges is the strong possibility that increased interdependencies among disparate technologies will "stiffen" industrial infrastructures and impede process innovation. This stiffness can be problematic - especially if it causes "sub-optimal choices to get ëlocked in' by widespread adoption" (Ayres 1994:36). Consider Frosch and Gallopoulos' following description of a successful industrial ecosystem:

> In such a system the consumption of energy and materials is optimized, waste generation is minimized and the effluents of one process - whether they are spent catalysts from petroleum refining, fly and bottom ash from [coal fired] electric power generation or discarded plastic containers from consumer products - serve as the raw material for another process (1990:98).

While "optimizing" waste cascades from coal-fired power plants and oil refineries would certainly offset other sources of material throughput, it would also re-enforce our dependence on highly dissipative energy sources that are by themselves largely responsible for many of the environmental crises that confront us. Can coal-fired power plants and oil refineries be part of an "optimized" industrial ecosystem? Only if optimized is narrowly defined. Indeed, the creation of "complex food webs between companies and industries" (Tibbs 1992:9) leads to a puzzling dilemma: Efforts to "minimize" material throughput by designing processes around existing waste streams (or designing waste streams for specific process needs) may "minimize" waste from the existing technological infrastructure at the cost of entrenching "sub-optimal," dirty technologies and thereby impeding a transition to more sustainable industrial practice - the very goal that IE alleges to promote.

VI. Omissions and Weaknesses

Efforts to realize Industrial Ecology's vision of sustainable industrial practice are thwarted not only by methodological deficiencies in IE's tools and broader dissonance between strategies and goals, but also by the omission of several aspects of our consumption predicament. Several important forms of material dissipation and the energy implications of closing material cycles both receive only passing attention. In addition, the IE literature reveals severe weaknesses in its analysis of social issues. In this section, we will address these oversights as they relate to each of IE's two goals.

Resource Dissipation: Missing The Target

While nearly every form of dissipative material throughput is addressed at some point in the IE literature, the relative emphases placed on various forms of dissipation do not appear to reflect their relative significance. The material throughput addressed in the IE literature is primarily non-fugitive, non-dilute, point source, industrial wastes and non-dissipative consumer products. Not surprisingly, these are exactly the type of emissions that can be reduced with the battery of tools put forth in the IE literature (i.e. changes that do not require fundamental shifts in consumption patterns).

As Ayres indicates, "the problem, in brief, is that wastes associated with dissipative consumption (of energy and goods) now exceed waste emissions from manufacturing processes per se by a considerable margin in most advanced economies.... intermediate goods manufacturing processes could be absolutely emission-free without having much beneficial impact on overall environmental loadings" (1991:6,7). The IE literature seldom addresses larger shifts in material use patterns that would be required to address material throughput associated with the use of dissipative products such as pesticides, fertilizers, decorative and protective coatings, lubricants, adhesives, inks, and friction bearing surfaces such as brake pads or tires that serve their purpose through irretrievable dissipation. Even more disturbing, the massive and highly dissipative point and non-point source emissions resulting from the combustion of fossil fuels receives only passing mention. We agree with Piasecki that "the number [one] problem facing the field of industrial ecology in the 1990s will be securing safe, clean, abundant alternatives to fossil fuels" (Piasecki 1992:875). The reluctance to address the use of fossil fuels reflects larger weaknesses in IE's handling of energy issues.

Energy Matters

While IE's goal of material closure is based on the model of material flows in natural ecosystems, it is rather odd that energy flows in natural ecosystems are largely neglected. In an introductory text on ecology, Kormondy writes that "...a one-way flow of energy constitutes one of the most important if not the cardinal principle of the ecosystem" (1969:17). If energy flows - not material flows - are "one of the most important" principles of a natural ecosystem, then IE should place at least equal emphasis on energy flows and how they change as ecosystems evolve. While the energy flows in an evolving ecosystem may seem more abstract than the material flows, they provide IE at least two important analogies. First, in any closed material cycle - whether "natural" or industrial - the flow of energy must remain open; energy cannot be "cycled." Since closing material cycles cannot eliminate the energy requirements of material provision, clean and non-dissipative sources of energy would be crucial even in a hypothetical closed-loop economy where all products and industrial wastes were recycled. Consequently, the importance of switching to renewable energy sources should receive far greater emphasis in the IE framework.

Secondly, the evolution of natural ecosystems from open material flows to closed material cycles is paralleled by significant changes in energy consumption patterns. Likewise, a shift in raw material processing activities from the virgin materials processing sector to a growing materials separation and reprocessing sector will produce dramatic shifts in energy demand. On one hand, recycling post consumer wastes such as aluminum cans yields large energy savings that are widely proclaimed among proponents of recycling but rarely addressed in the IE literature. On the other hand, recycling chemicals - such as solvents - from dilute industrial waste streams may result in net energy costs. The IE literature focuses almost exclusively on reducing open material flows and scarcely considers the associated shifts in energy flows.

Social Implications and Impediments

IE's dominant approaches to closing material cycles involve changing product design to reduce material intensity, and returning wastes to the economy as products. While these are important steps towards achieving closed material cycles, without addressing the social and economic forces driving consumerism and growing rates of product through-put, IE will end up chasing its tail. At best, it appears that IE's emphasis on reducing material content and material throughput will create a highly efficient "closed-loop", throw away society. In one notable exception, Stahel and Jackson (1993) have addressed the importance of increasing product longevity and emphasizing product service over product ownership. Most papers on IE, however, seem to accept growing rates of product throughput as our "modus operandi" and address the economic and social forces driving it only in passing if at all. This omission reflects a broader weakness in IE's analysis of socio-economic issues.

To move beyond purely technical questions, or even beyond closing materials cycles for specific industries, broader analyses of the social implications and impediments to IE is required. In general, the proponents of IE have chosen to ignore issues associated with bringing about an industrial restructuring under existing political and economic conditions. Those that do address social and political issues often gloss over them with simplistic calls for unleashing the invisible hand of the market, or reforming regulatory structures.

While the idea of "win-win" solutions for environmental problems is attractive, we would propose that current industrial-environmental problems (which IE is meant to address) will not be averted by simply promoting greater rationalization of industrial decisions, or more efficient market transactions. Other issues related to industrial restructuring need to be analyzed and reformed.

The role of the market in industrial development is one example of IE's weak analysis of socio-economic issues. Few IE proponents ask the simple question of whether anything in the market system (aside from it not being sufficiently "free" or comprehensive) may be causing industrial-environmental problems. Instead, most assume the market is part of the solution to problems, that via the profit motive, the environment can be protected and "sustainable industrial development" can be advanced. This assumption may be correct; however no evidence is presented to show causal relationships between levels of market freedom for instance, and implementation of IE. As Schnaiberg (1994) has argued, there are likely to be limitations to the promotion of IE concepts purely through capitalistic market structures, and furthermore, some functions of the market may be part of the problem and thus need to be regulated. If nothing else, the status quo will certainly place limitations on changes in industrial actions.

Government and industry leaders in the United States have for many years resisted efforts aimed at formulating and promoting "industrial policy." The accepted thinking in the U.S. is that the market alone should "coordinate" industrial decisions. From this perspective it is argued that individual firms have little control over what they produce but instead simply respond to consumer demands. Graedel and Allenby (1995:63) for instance, assert that "all industrial activity is a response to society's needs and wants." With demand for products exogenously established, producers are left only with the latitude to alter production methods.

IE proponents essentially accept a conception of consumer sovereignty, and advance IE only to serve the limited flexibility of constrained producers. This naive assessment discounts the power of a multi-billion dollar advertising industry that works to create and sustain "latent demands" for products that consumers previously didn't know they needed. Is there no feedback from industrial activity to consumer decisions? Is there no need for reducing or shifting demand for certain products? These questions receive only passing comment in the IE literature.

IE proponents focus their socio-political analyses on reforming regulatory structures that act as barriers to the implementation of IE (Gertler, Frosch, Lowe). The Resource Conservation and Recovery Act (RCRA) is singled out in particular as an impediment to waste exchange. Best Available Technology (BAT) standards are also criticized for their tendency to lock in end-of-pipe technologies and to deter process innovation. However, criticizing the EPA or policies that seem to impede IE does little to advance a path for actually moving IE forward. Few of the proponents of IE have analyzed the difficult changes necessary in regulatory structures, and the balancing of regulations for waste management (such as RCRA) with the desire to promote greater symbiosis in the industrial economy. Ehrenfeld's (1994) work on product policy stands out as a single example of clear policy analysis related to IE implementation.

Any economic or industrial restructuring, no matter what its purpose, will confront barriers and entrenched interests that try to restrict its success. As Schnaiberg notes "...despite their apparent interest in sustainable development, most treadmill actors are likely to offer substantial resistance to the actual policies that will promote genuinely sustainable development, except for those firms whose near-term profitability can be directly tied to such policies" (Schnaiberg 1994:2). The prescriptive parts of the IE literature generally ignore institutional inertia and the basics of organizational behavior that serve to block or slow change. Here again the attitude of the authors is simply that better information or better pricing will create a rationale that overpowers all existing interests.

Finally, IE's relationship to global economic changes and trends toward global production networks is left only to the imagination. As seems clear to most observers, the world is moving beyond "Fordist" systems of mass production. Flexible, agile, and even virtual corporations are the new buzzwords of production. Production networks are constantly changing, resulting in changes in suppliers of raw materials, locations of factories, and product lines. How does IE, and in particular the vision of linking the wastes from one factory to the inputs for another fit into these new operating parameters? As with a number of other issues, the IE literature has yet to address the realities of current global production systems (Kenney and Florida 1993; Sklair 1991).

VII. Conclusions - The Future of IE

Industrial Ecology offers an important set of goals and organizing principles for reforming industrial activities to reduce their adverse environmental impacts. The IE framework begins to fill a current void for analyzing industrial-environmental problems and for designing solutions to growing resource constraints and degradation of environmental quality. It is quite clear that industry, government, and public organizations need tools for better analysis and planning of environmental issues. However, while having the potential to provide these tools, IE is currently mired in its own ambiguity and weaknesses. As we have discussed, the five main critiques of IE are that: (1) it is poorly defined; (2) tools have methodological weaknesses; (3) strategies often don't support goals; (4) implementation to date does not reflect ideas expressed in the literature; and, (5) technical analysis of energy issues and socio-political analysis of means to transform industry are extremely limited. We will summarize these briefly and then propose steps to move beyond these impediments.

Early efforts to delineate Industrial Ecology have produced a wide variety of strategies and tools for achieving disparate visions of sustainable industrial development. IE, as a field, is in an inclusive phase where few authors have ventured to say what IE is not, thus leaving the field broad and vague. If its scope is not clarified, IE may succumb to the same ambiguity that has plagued the concept of sustainable development (Lele 1991).

The market strategies touted in the IE literature are problematic policy options that have been the subject of debate for decades. The cursory and overly optimistic treatment of market tools such as Pigovian taxes does not aid their advancement and simply avoids the difficult conflict between market approaches and IE's ostensible goal of changing the way we think about industry-environment interactions. The IE literature also supports the development and implementation of new design tools and procedures such as DFE. While any improvement in the environmental performance of industrial processes and products is certainly desirable, it remains unclear whether industry has sufficient motivation to broadly implement DFE and whether these design tools could produce unambiguous guidance even if they were used. In addition, our growing ability to estimate the broad environmental implications of minute changes in industrial practice seems to be leading many IE proponents in the wrong direction: larger questions about the sustainability of technological infrastructures (such as a transportation system that remains largely dependent on gasoline powered automobiles) risk being buried under a barrage of complicated yet relatively unimportant design tradeoffs (plastic versus aluminum radiator caps).

Efforts to cite existing examples of IE implementation fail to capture the central ideas expressed in the literature. Several process level modifications that reduce pollution and increase profits are described. While "pollution prevention" activities will certainly help advance IE, these projects do not capture the systems level approach that separates IE from the already large body of P2 literature. Where examples of systems level efforts are cited (such as the "industrial ecosystem" in Kalundborg, Denmark), the ability of cascading waste exchanges to reduce material throughput is extolled while the importance of closing entropy cycles and the potential for "stiffening" industrial infrastructures and thereby entrenching inherently dirty technologies are largely neglected.

Although energy flows are central to the operation and evolution of natural ecosystems, the IE literature seeks analogy only to the increasingly cyclical material flows of maturing ecosystems. Accordingly, the energy implications of closing material cycles and the importance of renewable energy sources receive only passing mention. IE also desperately needs to be fortified with serious social analysis regarding the impediments to changing current industrial practices. While authors from within private industry may accept that industry should be left alone with the market to solve industrial-environmental problems, few citizens or environmental groups are likely to accept this strategy. Ultimately, many of the issues addressed in the IE literature boil down to value judgments that society must address. As we have mentioned, many of the concepts within IE are not new. Nonetheless, the IE literature fails to examine the lessons of 1970's and 1980's attempts to reform industry. We are skeptical that simple changes in information or market structures will overcome the barriers that impeded past efforts. Society at large increasingly shares this skepticism. Environmental organizations for example, have not embraced IE partly due to their distrust of technological solutions to technologically created problems. These concerns must be addressed if IE is to be accepted beyond the realm of industry environmental managers.

Moving Forward

Our conclusion after critically reviewing the literature is that IE can be advanced on several levels, from incremental changes to more transformative efforts. On all levels it will be necessary to expand debate and research. We would propose a three stage approach to moving IE forward. First, focusing and refining existing IE concepts. Second, experimenting with the implementation of IE concepts. Third, creating mechanisms for discussion and debate regarding the transformation of industrial activity that includes a broad range of actors and interested parties.

The first level of work focuses on strengthening existing tools and strategies for implementing IE. A critical reading of IE leaves the impression that efforts to incorporate more information into product design and incrementally adjust market signals will not move society appreciably towards sustainable industrial development. We feel nonetheless that it will be valuable to attempt to refine IE tools. Design tools such as DFE can help reduce industry's burden on the environment and should be cautiously advanced. We must, however, acknowledge their limitations: while new approaches to design can realize incremental reductions in the environmental burden of products and processes, DFE will not advance the larger technological and cultural shifts in industry practice that we believe are necessary to achieve IE's broader goals. The developers of DFE must strive to avoid three crucial pitfalls: linking DFE with unrealistic goals, pouring resources into relatively unimportant detail, and incrementally improving (and thereby entrenching) inherently dirty technologies when cleaner alternatives are available.

More rigorous consideration of the thermodynamic implications of closing material cycles is also needed. The almost complete omission of energy issues - and especially the importance of advancing renewable energy sources to reduce dissipative material throughput - strongly detracts from IE's strength and credibility. Finally, unrealistic and misleading concepts such as Ecofeedback do more to thwart IE than advance it and should be vigorously discarded. Along these lines, IE proponents should begin the process of determining what IE is not; that is to discard vague, overly optimistic, and even corrupt conceptions of the field. IE's vision and goals should be debated openly and vigorously. This will serve to focus the concepts and to separate those interested in transformative changes from those interested in putting a new face on the status quo.

The second level of work should help to turn theories and visions into implementable projects. We believe that it will be necessary to experiment with (and study) the implementation of IE concepts initially on a small scale. A role for government may be the promotion and assessment of IE concepts in projects such as "brownfield" re-development efforts, Eco-parks, and regional industrial metabolism studies. Actual implementation efforts should be monitored closely in the coming years as IE projects are begun. Research should focus on the following questions: What role did economic motivation, government policies, and the local community have in the formation of existing "industrial ecosystems" such as the one found in Kalundborg, Denmark and the eco-park projects in Brownsville, Texas and Baltimore, Maryland? To what extent have existing eco-park projects reduced material throughput and material dissipation, and what have been the resulting changes in energy demand and energy efficiency? To what extent has the formation of existing industrial ecosystems reduced the flexibility of process innovation? Finally, what are the primary barriers inhibiting the expansion and replication of these projects?

Smaller research projects and feasibility studies on implementing IE in different settings will also be important to advancing the concepts.

The implementation of IE concepts at the firm level is more problematic. If IE is to be successful it must move from incremental change (and simple pollution prevention) to a more fundamental re-thinking and re-design of products and processes. We, however, are skeptical that a critical re-thinking of industrial practices will come from industry until pressures for change are much stronger. These pressures would include economic incentives and disincentives, legal pressures, and social input into industrial decision-making. It is clear that society must first embrace IE concepts if this sort of social pressure is to be generated to push for changes in industrial-environmental relations.

This brings us to the third level of work. IE's acceptance by the public and environmental organizations will require the development of mechanisms of social input into decisions about the restructuring of industry. As we have alluded to throughout the paper, many of the underlying decisions necessary for the promotion of IE (and DFE and LCA more narrowly) are based on social value judgments. We agree with Schnaiberg that "we need more socially, economically, and politically integrated ways to observe, assess, and resist the institutions of the treadmill, if we are to be able to initiate and maintain a trajectory of sustainable development" (Schnaiberg 1994:3). IE will not be successful if industry alone embraces its concepts and techniques. Rather, it will be necessary to create social institutions and mechanisms that serve to foster the goal of balancing industrial activity, the environment, and equity concerns. Our belief is that this type of balance is more likely to occur at the local level where citizens have vested interests in balancing industrial activities with environmental quality.

As we approach the 21st century, a paradigm shift will be required for industry and the environment to move toward balance. This shift will require a re-thinking of more than just waste flows, pollution taxes, and information databases. It will require a change in values, in mechanisms of control over technology, and in the functioning of the economy. "Sustainable industrial development" represents a critical goal towards which industry, government, and the public should strive. However, this goal will remain ever elusive unless concrete steps are taken to evolve IE gradually towards implementable solutions to industrial-environmental problems.

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1. We will discuss IE within a narrow view of industrial activity, analyzing its relevance primarily to manufacturing operations.

2. Although the total change in entropy associated with any real (irreversible) process must be positive, here we are addressing only changes in the entropy of materials. The entropy of a material may be reduced, but doing so requires the "consumption" of energy - or more precisely exergy - and will produce a larger increase in the entropy of the surroundings associated with an expulsion of lower quality energy (Brodyanski, et al. 1994, Lewis and Randall 1961).